

1N-35  
131954  
p. 31

# Experimental Testing of Four Correction Algorithms for the Forward Scattering Spectrometer Probe

Edward A. Hovenac  
*Sverdrup Technology, Inc.*  
*Lewis Research Center Group*  
*Brook Park, Ohio*

John R. Oldenburg  
*National Aeronautics and Space Administration*  
*Lewis Research Center*  
*Cleveland, Ohio*

and

James A. Lock  
*Cleveland State University*  
*Cleveland, Ohio*

October 1992

Prepared for the  
Lewis Research Center  
and Department of Transportation  
Federal Aviation Administration

**NASA**  
National Aeronautics and  
Space Administration

N93-13307

Unclas

G3/35 0131954

(NASA-TM-105906) EXPERIMENTAL  
TESTING OF FOUR CORRECTION  
ALGORITHMS FOR THE FORWARD  
SCATTERING SPECTROMETER PROBE  
(NASA) 31 p



U.S. Department  
of Transportation

**Federal Aviation  
Administration**

## NOTICE

This document is disseminated under the sponsorship of the U.S. Department of Transportation in the interest of information exchange. The United States Government assumes no liability of the contents or use thereof.

The United States Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the objective of this report.

Experimental Testing of Four Correction Algorithms for the  
Forward Scattering Spectrometer Probe

Edward A. Hovenac  
Sverdrup, Technology, Inc.  
NASA Lewis Research Center Group  
Cleveland, OH 44135

John R. Oldenburg  
NASA Lewis Research Center  
Cleveland, OH 44135

James A. Lock  
Physics Dept., Cleveland State University  
Cleveland, OH 44115

Abstract

Three number density correction algorithms and one size distribution correction algorithm for the Forward Scattering Spectrometer Probe (FSSP) were compared with data taken by the Phase Doppler Particle Analyzer (PDPA) and an optical number density measuring instrument (NDMI). Of the three number density correction algorithms, the one that compared best to the PDPA and NDMI data was the algorithm developed by Baumgardner, Strapp, and Dye (1985). The algorithm that corrects sizing errors in the FSSP that was developed by Lock and Hovenac (1989) was shown to be within 25% of the Phase Doppler measurements at number densities as high as 3000 /cc.



## TABLE OF CONTENTS

	Page
EXECUTIVE SUMMARY .....	v
1. INTRODUCTION .....	1
2. EXPERIMENTAL SETUP .....	1
3. THE FSSP CORRECTION ALGORITHMS .....	4
4. COMPARISON OF THE NUMBER DENSITY ALGORITHMS .....	11
5. COMPARISON BETWEEN THE FSSP CORRECTED SIZE AND THE PDPA .....	13
6. CONCLUSION .....	14
7. REFERENCES .....	23

PRECEDING PAGE BLANK NOT FILMED

## LIST OF FIGURES

Figure		Page
2.1	Experimental setup comparing FSSP with PDPA	3
3.1	Oscilloscope traces from FSSP	6
3.2a	Uncorrected number density vs activity	8
3.2b	L&H number density correction curve	8
3.3	L&H number density correction curves for two different values of laser length $L$	10
4.1	Comparison of number density correction curves	12
4.2a	Comparison of various corrections vs PDPA data	15
4.2b	Ratio of FSSP number density to PDPA number density	16
4.2c	Comparison of various corrections vs NDMI data	17
4.2d	Ratio of FSSP number density to NDMI number density	18
5.1a	Percent difference between FSSP average diameter and PDPA average diameter	19
5.1b	Percent difference between FSSP MVD and PDPA MVD	20
5.2a	Corrected FSSP MVD data shows no increase with number density	21
5.2b	PDPA MVD data shows a decrease with number density	22

## EXECUTIVE SUMMARY

The Forward Scattering Spectrometer Probe (FSSP) is an optical droplet sizing instrument that is used for measuring the diameter of micron size water droplets. Although the FSSP is the most widely used droplet sizing instrument in icing research, corrections are required to its measurements under conditions of high number density. The Phase Doppler Particle Analyzer (PDPA) is an optical droplet sizing instrument that has gained wide acceptance in spray nozzle and combustion diagnostics research. The purpose of this report is to compare FSSP data employing several correction algorithms with data taken by the PDPA and by an optical number density measuring instrument (NDMI). The comparison provides information on how closely the FSSP data agrees with the PDPA and the NDMI and how much the agreement is improved by the correction algorithms considered.

Three number density correction algorithms and one size distribution correction algorithm for the FSSP were compared with data taken by the PDPA and the NDMI. The number density algorithms tested were the activity correction developed by Particle Measuring Systems (ref. 3); a statistical correction developed by Baumgardner, Strapp, and Dye (ref. 4); and another statistical correction developed by Lock and Hovenac (ref. 12). A size distribution correction algorithm developed by Lock and Hovenac was also tested (ref. 15).

Of the three number density correction algorithms, the one that most closely agreed with the PDPA and NDMI data under conditions of very high number density was the algorithm developed by Baumgardner, Strapp, and Dye. The algorithm that corrects sizing errors in the FSSP that was developed by Lock and Hovenac was shown to be within 25% of the Phase Doppler measurements at number densities as high as 3000 /cc.



## 1. INTRODUCTION

The Forward Scattering Spectrometer Probe (FSSP) is an optical droplet sizing instrument that is used for measuring the diameter of micron size water droplets (ref. 1). At the NASA Lewis Research Center the FSSP is mounted on research aircraft and flown through icing clouds for the purpose of characterizing these clouds. The instrument is also used for measuring droplet diameters in the NASA Lewis Icing Research Tunnel (ref. 2). It has been known for some time that measurement errors in the FSSP increase as number density increases (refs. 3,4) and these errors can become unacceptably large if the number density increases beyond several hundred droplets per cubic centimeter (ref. 5). Such conditions of high number density are not unusual for the IRT and thus correction algorithms are needed to improve the FSSP data. The purpose of this report is to compare FSSP data employing several correction algorithms with data taken by another droplet sizing instrument, the Phase Doppler Particle Analyzer (PDPA) (ref. 6) and an optical number density measuring instrument (NDMI).

## 2. EXPERIMENTAL SETUP

The PDPA is an optical droplet sizing instrument that has gained wide acceptance in the spray nozzle and combustion diagnostics communities (ref. 7). The principle of operation of the PDPA is significantly different from that of the FSSP. The FSSP determines the diameters of droplets by measuring the intensity of light scattered by a droplet as it crosses a focused laser beam. The intensity of the scattered light contains the information about the droplet's size. The PDPA makes use of a pair of crossed laser beams similar to those used for laser Doppler velocimetry (LDV). If a droplet is present in the region of the intersecting beams, it creates a scattering pattern of bright and dark fringes. The spacing of these fringes contains the information about the diameter of the droplet. In addition the PDPA measures the velocity of the droplets using standard LDV techniques (ref. 8). For the comparison test, the PDPA size range was set to 1.3-47  $\mu\text{m}$  to closely match the 2-47  $\mu\text{m}$  range of the FSSP.

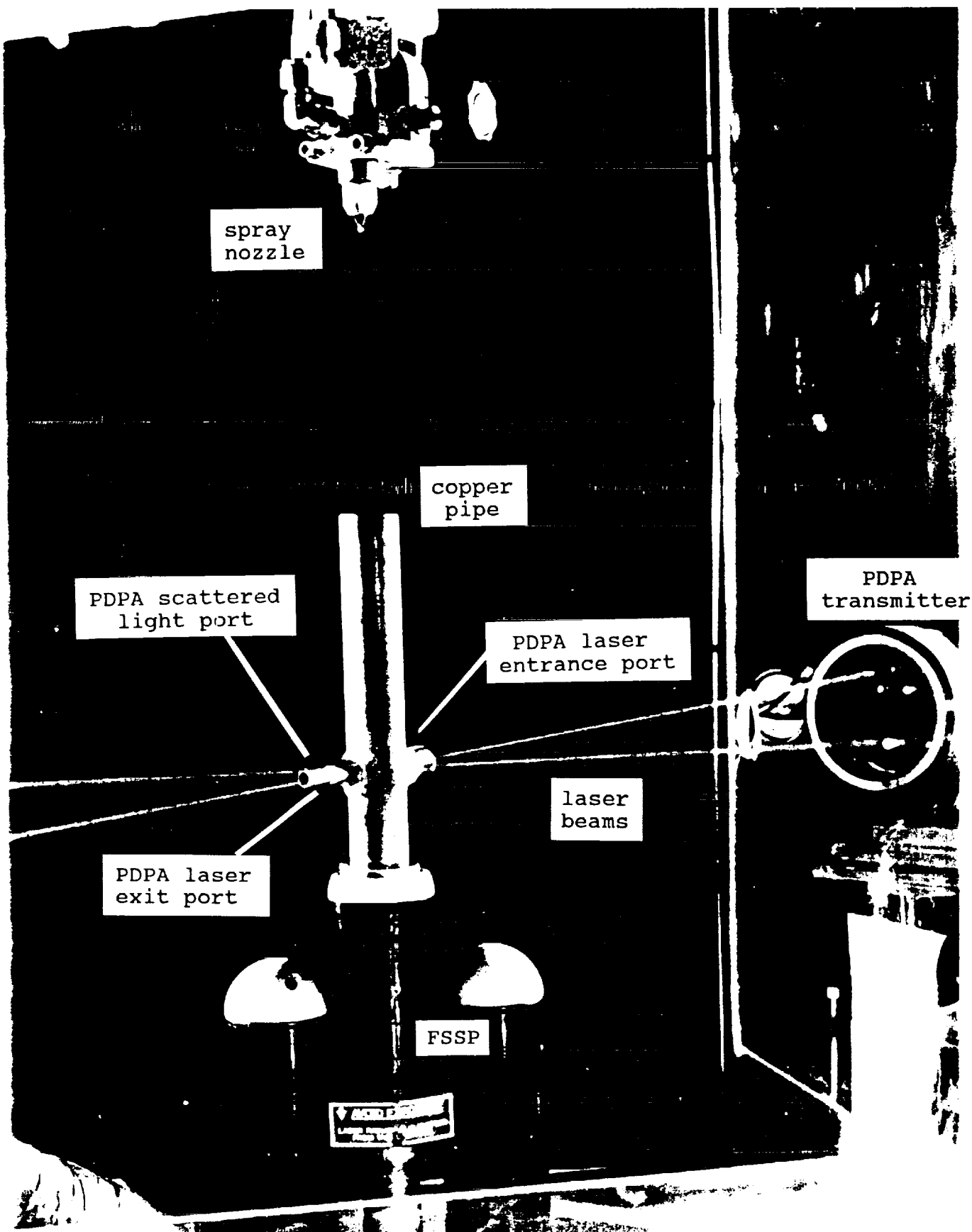
The NDMI is a prototype instrument designed to measure only droplet number density. It has some features of both the FSSP and the PDPA. Like the FSSP, it detects the scattered light from a droplet as it passes through a focused laser beam. However the optical collection angles of the NDMI are similar to those of the PDPA ( $\sim 30^\circ$ ). Also, the NDMI utilizes a slit aperture like the PDPA does to define a small probe volume. The small probe volume of the instrument makes it possible to measure high number densities ( $> 10000$  per cc). Measurements were made with the NDMI to help verify the number density measurements made by both the FSSP and the PDPA in dense sprays.

The experiment was designed so that simultaneous measurements of a water spray could be made by either the FSSP and the PDPA or

the FSSP and the NDMI. Because of space restrictions, the probe volume of the two instruments making the measurement needed to be separated by approximately 16 cm. A photograph of the experimental setup for the FSSP and the PDPA is shown in figure 2.1. A similar arrangement (not shown) was used for the FSSP and the NDMI. A 2.54 cm diameter copper pipe 37 cm long was inserted into the flow straightening tube of the FSSP. The copper pipe was wrapped with duct tape in the region where it fit into the FSSP so that it was centered and it fit snugly in the flow straightening tube. A set screw installed on the FSSP was used to insure that the copper pipe would not move. The pipe had two holes drilled in it that acted as entrance and exit ports for the FSSP's laser beam. The entrance port was 2.4 mm in diameter and the exit port was 8 mm in diameter. The 8 mm exit port (which corresponds to a scattering angle of  $17.5^\circ$ ) was large enough to ensure that the light scattered from the droplets would not be vignetted (i.e. cutoff) by the port. The bottom of the pipe was connected to a wet/dry vacuum cleaner via a flexible hose. The vacuum source was adjusted to draw the droplets through the copper pipe at approximately 24 m/s. This provided a droplet velocity greater than the FSSP minimum velocity of 10 m/s and yet slow enough so that any velocity dependent sizing errors (ref. 9) would be minimal.

The distance from the top of the copper pipe to the PDPA laser ports was 12 cm. This distance was long enough to ensure that all the droplets that entered the copper pipe had adequate time to accelerate to the flow velocity. Three ports were required on the copper pipe for the PDPA. The first one was for the entrance of the laser beams, the second was for the exit of the beams, and the third port was located at  $30^\circ$  relative to the laser beams and provided collection of the scattered light by the PDPA receiving optics. The reason for providing an exit port for the laser beams was to avoid unnecessary reflections inside the pipe which would cause a large background light level. Fittings 2-3 cm long were placed over the ports to reduce the possibility of droplets entering through the laser port rather than the top of the pipe. Such droplets would be moving slower than the rest of the flow and could cause measurement discrepancies. As with the FSSP laser ports, these ports were large enough to ensure that neither the laser beams nor the scattered light would be vignetted by the copper pipe and the fittings.

Droplets were sprayed from above the copper pipe using a Sonicore nozzle manufactured by Sonic Development Corporation (ref. 10). A droplet size distribution (number of droplets as function of diameter) which was well within the range of the instruments was achieved by varying the air pressure and water flow rate into the nozzle. Once a satisfactory droplet distribution was achieved, these parameters were typically left unchanged throughout the test. The number density was varied by moving the nozzle relative to the copper pipe. Nozzle positions 5-10 cm directly above the pipe produced very high number densities while nozzle positions 60 cm from the pipe or off-axis nozzle positions produced very low number densities.



2.1 Experimental setup for comparing the FSSP with the PDPA.

The FSSP data was collected using a data acquisition system from SPEC, Inc. (ref. 11) that consisted of a board which plugged into a slot on an IBM PC/AT microcomputer. Data collection software provided by SPEC was integrated with custom software that implemented the various data correction algorithms. The SPEC software was used in a mode that collected data continuously and sent files to the microcomputer's hard disk drive. Each file represented one minute of FSSP data and the files were resolved in one second increments. Two, three, or four one-minute files were combined into one data set which typically consisted of several hundred thousand measured droplets and was used to calculate one data point such as the measured number density or the measured average diameter.

The PDPA was set to measure 50,000 droplets before terminating a measurement session and calculating a data point. The PDPA measurement sessions (data collection plus processing time) typically took two to four minutes. The measurement sessions for the PDPA and the FSSP always started within one to two seconds of each other but didn't necessarily terminate at the same time since the PDPA measurement sessions rarely took an integer number of minutes.

Data collection for the NDMI did not require the use of a computer. The output of the NDMI's photomultiplier tube was connected to conditioning electronics and routed to a frequency meter. The frequency meter was set to count the number of pulses (i.e. droplets crossing the probe volume) per minute. The frequency meter was set to average over one minute intervals that corresponded to the one minute intervals of the FSSP data sets. To determine the calibration factor that would convert counts per minute into droplets per cc, a series of measurements was made in low number density sprays (< 80 droplets per cc) with the NDMI and the FSSP. NDMI frequency vs. FSSP number density was plotted and the slope of the data was determined using a linear regression algorithm. The slope was used as the calibration factor for the NDMI throughout the test. It was assumed that the FSSP could accurately measure number density in such a dilute spray.

### 3. THE FSSP CORRECTION ALGORITHMS

There are a number of algorithms which have been formulated to correct FSSP data. This paper addresses those algorithms that correct FSSP measurement errors that are a result of high number density. The ones which were included in the test are denoted by bold print below.

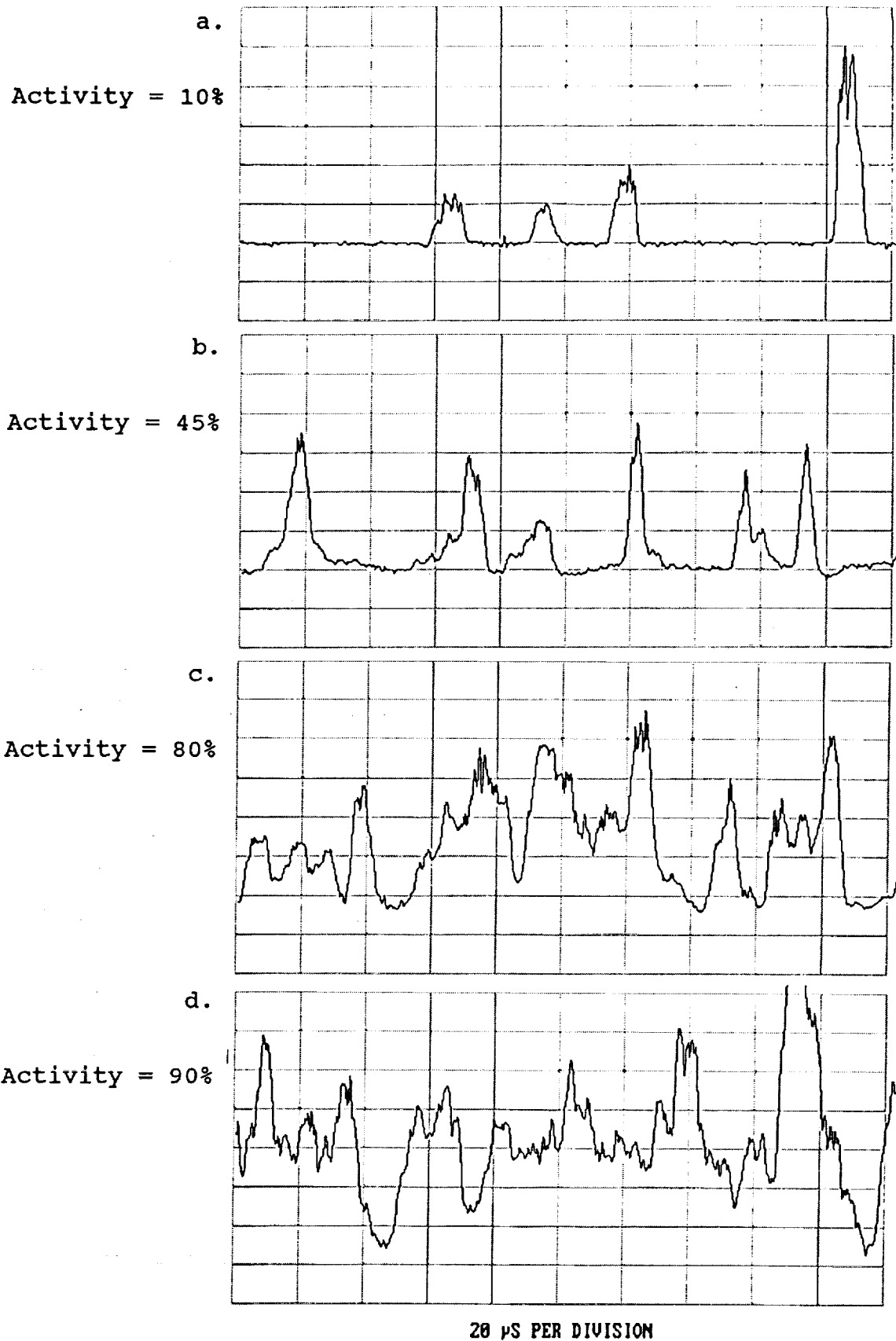
The first correction algorithms that were developed for the FSSP were designed to correct number density errors (refs. 3,4). These algorithms will be denoted throughout as the **activity number density correction** and the **BSD number density correction** (named after the authors Baumgardner, Strapp and Dye). In 1989 a number density correction algorithm was published by Lock and Hovenac (ref. 12). This will be referred to as the **L&H number density correction** algorithm. A short time later another number density

correction algorithm by Brenguier and Amodei (refs. 13,14) was also published. Both of these algorithms are refinements of the BSD correction algorithm. Also, two algorithms which correct the errors in measured size that result from large number densities have been published: first by Cooper (ref. 5), then by Lock and Hovenac (ref. 15). The latter of these will be denoted as the **L&H total distribution correction**.

There are two reasons correction algorithms are needed for the FSSP. First, the electronics in the FSSP need a period of time to analyze the light scattered by a droplet. During this period, called the dead time, the FSSP is insensitive to additional droplets crossing the laser beam. Thus, the FSSP can undercount the number of droplets crossing the probe volume. If this occurs, the number density, which is calculated from this value, is lower than the actual number density. This error does not effect the measured diameter of the droplets and it does not skew the measured droplet distribution.

Correction algorithms are also needed when many droplets are in the laser beam simultaneously and scatter light into the instrument's detector. The light from these droplets combines and is detected as a single larger droplet. Thus counting and sizing errors occur. These are known as coincidence effects and are illustrated in figure 3.1. The four plots in the figure are oscilloscope traces from the sizing detector of the FSSP for four different activity levels. The activity is a measure of the percent of time the FSSP is detecting and analyzing droplets. Thus it increases as number density increases. In figure 3.1a the activity was measured to be 10%. There are four well defined voltage pulses that represent three small droplets followed by a larger one crossing the laser beam. Note that the pulses (i.e. droplets) are clearly separated. The FSSP would be able to count and measure each of these droplets correctly. In figure 3.1b the number density was increased by repositioning the spray nozzle closer to the instrument and the activity was measured to be 45%. Note that some of the pulses are now overlapping. In the cases where a smaller and a larger pulse overlap, the FSSP will only measure the larger droplet. In figure 3.1c and 3.1d the number density was further increased to produce activity levels of 80% and 90%. In these cases the combined effect of many smaller droplets is to raise the signal of the larger ones. This effect is to skew the measured distribution to the larger sizes.

One characteristic of correction algorithms is that they require values for certain parameters which describe the instrument. The parameters may be determined experimentally as for the case of the k-factor used in the activity correction algorithm. In the more sophisticated algorithms many parameters are required such as laser beam diameter, depth of field and electronic dead times. The values of these parameters are usually available in the instrument manual or could be measured by the user (ref. 16). However there are other parameters that cannot be directly measured. Determination of these parameters is discussed below.



3.1 Oscilloscope traces from the FSSP signal detector for four different levels of activity.

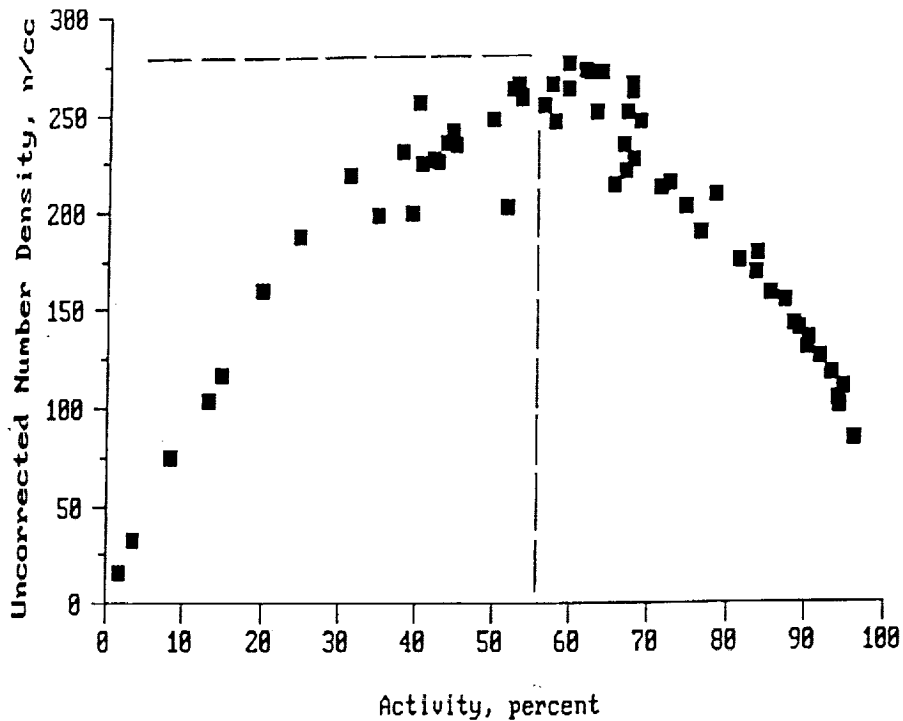
The functions describing the BSD and the L&H number density correction algorithms are multivalued. For a given measured number density two solutions for the correction algorithm exist. The measured activity is used to determine the correct solution. For example if the measured activity is below a predetermined activity value, then one solution is used. If the measured activity is above this predetermined activity value then the other solution is used. In order to determine this activity value, it is necessary to understand what feature in the FSSP causes the BSD and the L&H correction functions to be multivalued.

Consider making measurements in a cloud or a spray that has a very low number density. Under this condition the FSSP is able to make accurate number density measurements. As the number density in the cloud increases, the FSSP begins to experience counting losses and the measured number density increases at a slower rate than does the actual number density. At still higher number densities the counting losses dominate to such an extent that the measured number density will decrease and approach zero as the actual number density increases. Thus if the FSSP is reporting a low number density it could be because the actual number density really is low, or the actual number density is very high and the dead time and coincidence errors are causing the FSSP to undercount. The measured activity can be used to determine which case is actually occurring and determine whether to apply a small correction or a large one to the measured number density.

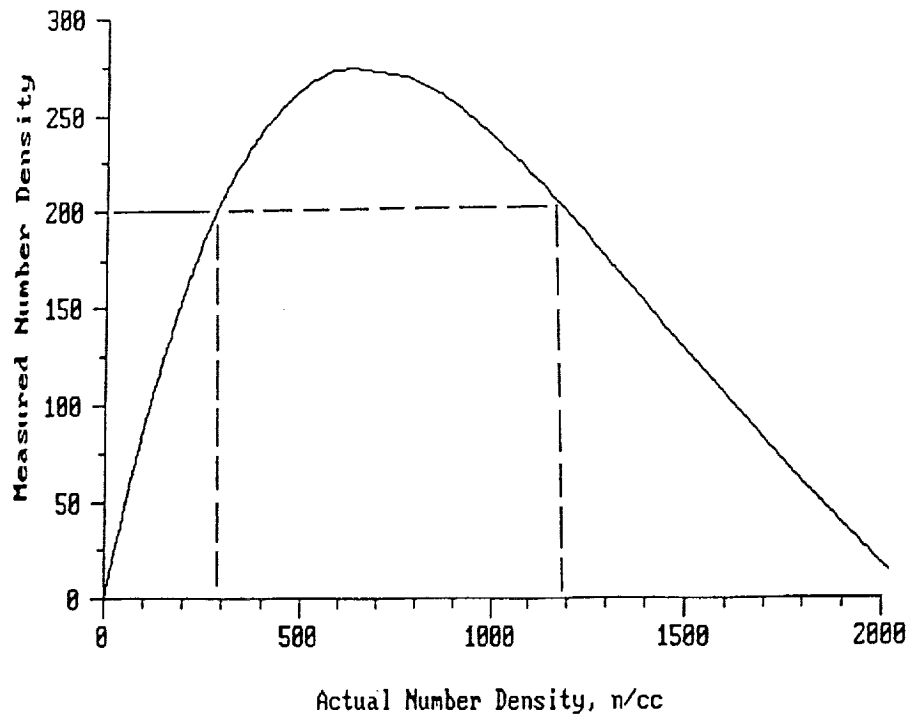
Figure 3.2a-b illustrates how activity can be used to determine the solution for the correction functions. Figure 3.2a is a plot of the FSSP's uncorrected number density as function of activity (this is experimentally measured data). Figure 3.2b is the FSSP's measured number density as a function of actual number density (this curve was calculated from eq. 46 in ref. 12). This plot represents a model of how the FSSP will measure the number density as a function of the actual number density. The data in the plot represents the correction curve used with the L&H algorithm. It also illustrates the multivalue nature of the correction function. A measured number density of 200 /cc could be corrected to a value of 279 /cc or a value of 1190 /cc. Using the data in figure 3.2a one can see that for this FSSP, the measured number density peaks at activity values of approximately 55%. Thus when using the correction function shown in figure 3.2b the left hand side of the correction curve is to be used if the measured activity is less than 55% and the right hand side is to be used if the measured activity is greater than 55%. This value of 55% activity or the "activity where the maximum measured number density occurs", will vary from instrument to instrument depending on the optical and electronic configuration of the instrument and it will also change for different droplet velocities.

Another parameter that needs to be determined is a quantity called the exposed laser beam length. This parameter appears in both the BSD and the L&H algorithms. The exposed laser beam length is the length of the laser beam exposed to the droplets. BSD and L&H define this length slightly differently. In one case the depth

a



3.2a Uncorrected number density as a function of activity. The peak value of this data is approximately 280 /cc. This occurs at an activity level of approximately 55%

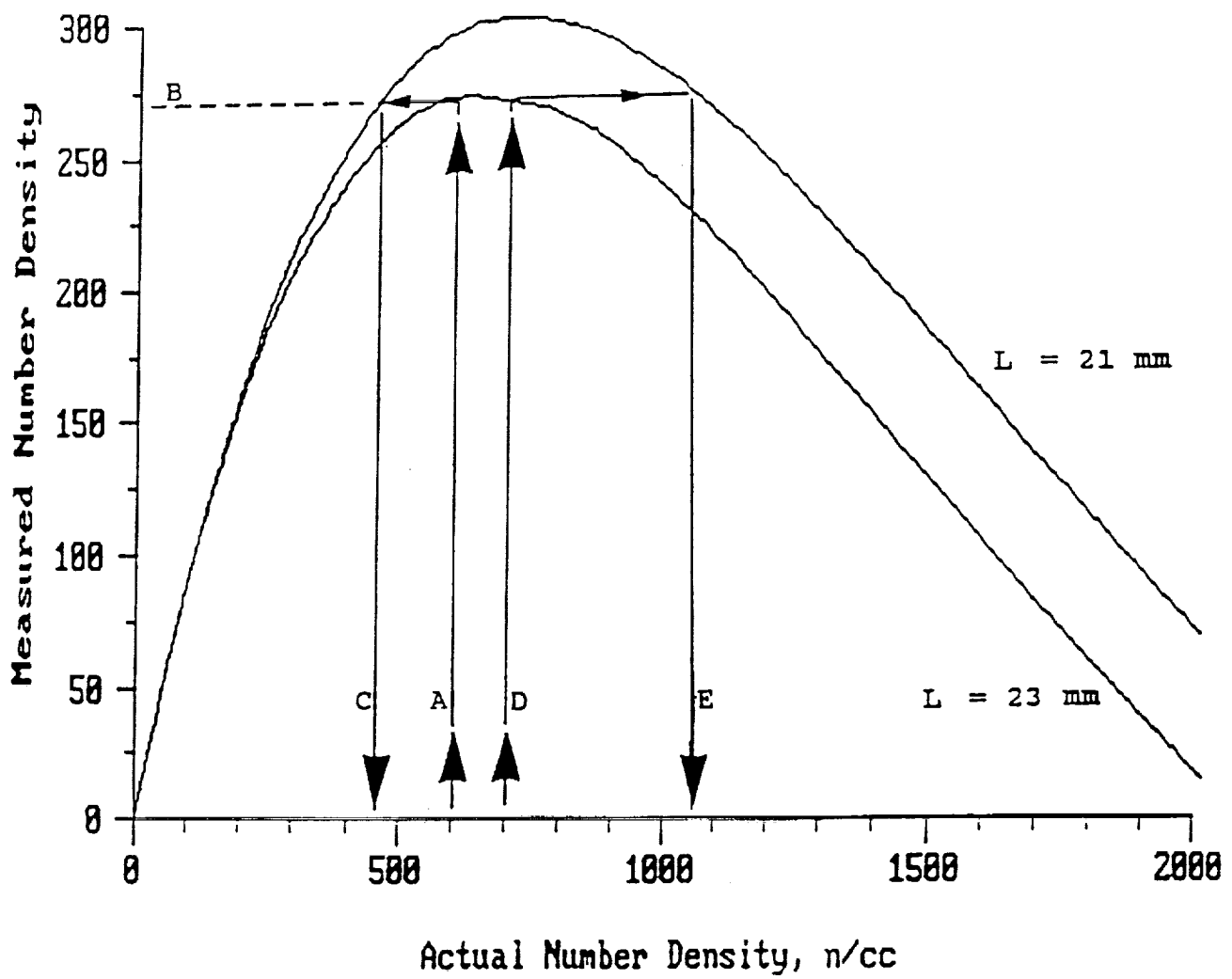


3.2b Representation of the L&H number density number density correction curve. A measured number density of 200 /cc could be corrected to a value of 279 /cc or 1190 /cc depending on whether the measured activity is below 55% or above 55%.

of field is included in the length and in the other case it is not; also different symbols are used ( $L_1$  vs.  $L$ ). This parameter is important because droplets that simultaneously cross the laser beam in this region will scatter light onto the FSSP's detectors and cause coincidence errors. The intensity of the scattered light from a droplet in this region diminishes if the droplet is far from the center of the depth of field or if the droplet is small. Thus a distinct boundary for the laser beam length does not exist. The values used in the BSD and the L&H correction algorithms for the laser beam length therefore are estimations.

A short time after taking data it was discovered that using the published estimates for the laser beam length was causing some obvious errors in the corrected number density. The data showed that the corrected number density jumped abruptly at a certain value (for both the BSD and the L&H algorithms) as the actual number density smoothly increased. A different method for determining the laser beam length resolved this discontinuity. Recall that the number density correction algorithm is a mathematical model of how the FSSP will measure number density as a function of the actual number density. This was shown graphically in figure 3.2b. Details of the shape of this curve are governed by the particular mathematical model of the instrument that was used and the values of the various parameters assumed for that model. For example, if different values for the laser beam length are used in the equations describing the instrument, the curve will change as shown for the two curves plotted in figure 3.3. Assume for a moment that the top curve in figure 3.3 is used to correct the measured number density but the bottom curve is a more accurate model of how the FSSP will measure the number density. At an actual number density of 600 /cc the bottom curve shows that the FSSP will measure 274 /cc (A→B) and the correction algorithm (top curve) will correct this up to 461 /cc (C). Now assume that the actual number density is increased to 700 /cc (D) causing the activity to increase to a value larger than 55% (i.e. the right side of the correction curve will be used). The data in figure 3.3 shows that the FSSP will measure approximately the same number density as before (B) but since the activity passed the 55% level, the corrected number density will jump to 1063 /cc (E). Thus, a relatively small increase in the actual number density (600 to 700 /cc) causes a large jump in the corrected number density (461 to 1063 /cc) when the activity increases beyond a preset value. It was precisely this ill-conditioned nature of the correction algorithm that produced the previously mentioned abrupt jump in the corrected data.

Figure 3.2a was used to determine the value for the laser beam length that would minimize this discontinuity. As can be seen from the data, the maximum measurable number density for the NASA Lewis FSSP (at 24 m/s) is approximately 280 /cc. As a result the laser beam lengths on both the BSD and the L&H number density correction algorithms were adjusted so that the equation describing the correction function also had a peak value of 280 /cc.



3.3 L&H number density correction curves for two different values of the laser length  $L$ .

Table 1: Values of the various constants used in the correction algorithms.

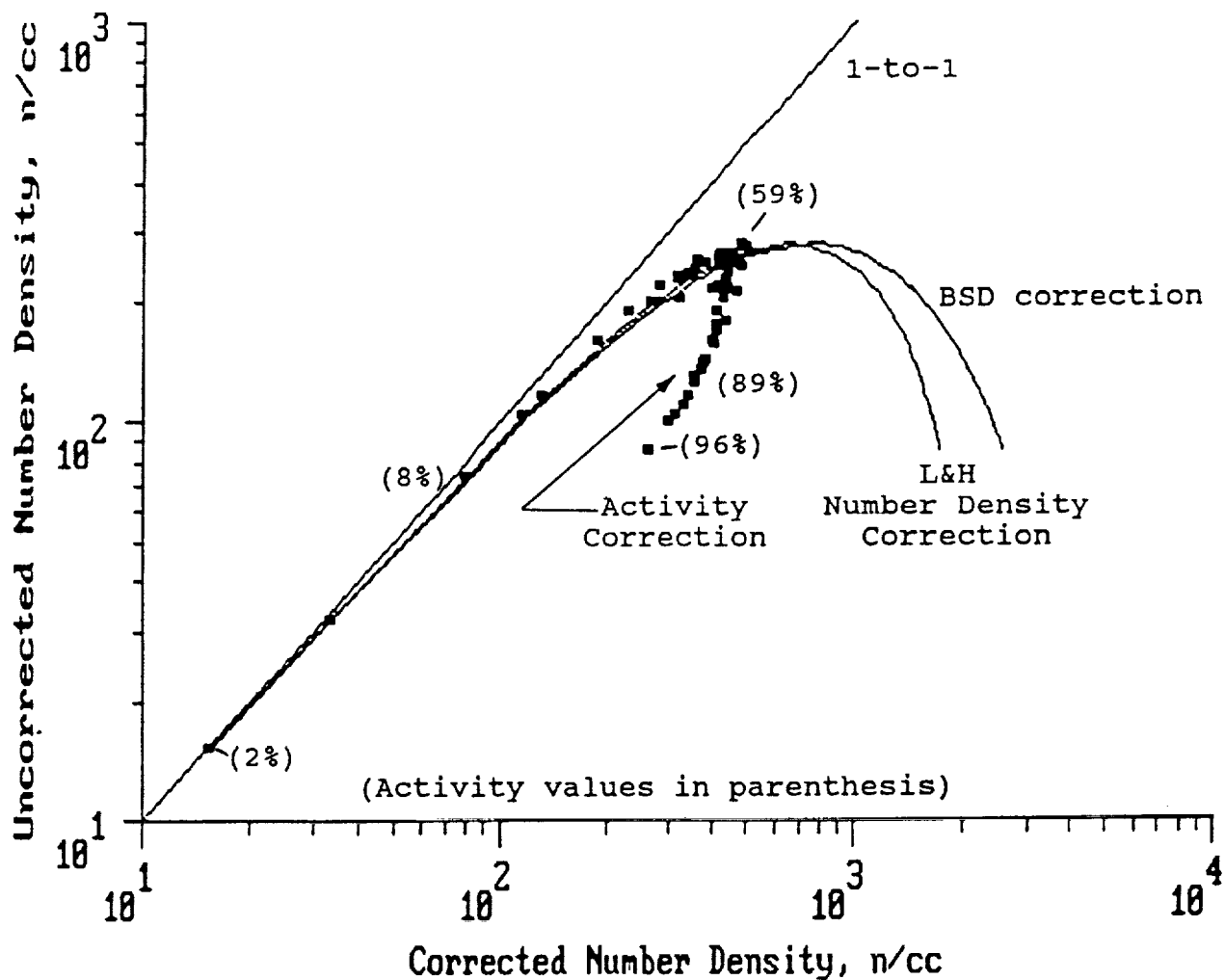
Correction Algorithm	Values of Constants Used			
Activity Number Density Correction	$k = 0.7$			
BSD Number Density Correction	$\tau_2 = 5.57 \mu s$ $W = 240 \mu m$	$\tau_3 = 1.58 \mu s$ $L_1 = 27.0 mm$	$L_0 = 2.74 mm$ $v = 23.6 m/s$	
L&H Number Density Correction	$\tau_s = 5.57 \mu s$ $d = 240 \mu m$	$\tau_f = 1.58 \mu s$ $L = 23.0 mm$	$L_0 = 2.74 mm$ $v = 23.6 m/s$	
L&H Total Distribution Correction	$\tau_s = 5.57 \mu s$ $d = 240 \mu m$ $L_1 = 9.0 mm$	$\tau_f = 1.58 \mu s$ $L = 23.0 mm$ $L_2 = 14.0 mm$	$L_0 = 2.74 mm$ $v = 23.6 m/s$	

Table 1 shows the values of the parameters used for the different algorithms. The definitions of the various parameters are given in the respective references. Note that the value needed for the BSD correction was 27 mm for  $L_1$  which is actually longer than the entire exposed laser beam. Also BSD's  $L_0$  constant was not needed because the droplet velocity mandated use of BSD's eq. 4.15 (ref. 4) which does not depend on  $L_0$ . The value of  $L_2$  for the L&H total distribution correction algorithm was arrived at by measuring  $L_0$  and  $L_1$  using a rotating pinhole device (ref. 17) and using eqs. (7) and (8) (ref. 15) to calculate the value of  $L_2$ .

#### 4. COMPARISON OF THE NUMBER DENSITY ALGORITHMS

A comparison of the number density correction curves for the activity correction, the L&H correction, and the BSD correction is shown in figure 4.1. These curves were calculated using the parameters of Table 1. There are several features to note about these curves. First, they all follow the one-to-one line fairly closely below number densities of approximately 100 /cc. This indicates that only very small corrections are needed in this region. At corrected number densities above several hundred per cubic centimeter the correction curves deviate greatly from the one-to-one line. Most notable is the activity correction which turns back toward lower values of the corrected number density. The BSD and the L&H corrections are quite similar to one another, the major difference being the magnitude of the correction for very high number densities. At number densities above 800 /cc, the BSD algorithm shows a larger correction than the L&H algorithm.

Figure 4.2a shows plots of the uncorrected number density, the activity correction, the BSD correction and the L&H correction as a function of the measured PDPA number density. Note that all of the curves deviate from the one-to-one curve at different points and that the BSD curve follows the one-to-one curve the best above



4.1 Comparison of the number density correction curves calculated from the activity correction, the BSD correction, and the L&H correction.

1000 /cc. Also note that there are discontinuities in the BSD and the L&H corrections at number densities of approximately 700 /cc. Fine tuning of the value used for the laser beam length would probably reduce these discontinuities. However, such adjustments would be based on the PDPA data and such data is not available to most FSSP users.

Figure 4.2b shows the same data as figure 4.2a except that the ordinate is the ratio of the FSSP number density to the PDPA number density. This shows the errors associated with the various algorithms. As can be seen in the figure, the correction algorithms do not eliminate the error, they only reduce it and thus they extend the usable range of the FSSP number density measurements. Also, this estimation of the error is based on the PDPA data which is subject to measurement errors as well.

Figures 4.2c-d show the comparison between the FSSP and the NDMI. These plots are similar to figures 4.2a-b and again show that the BSD correction is closer to the one-to-one curve at higher number densities than the L&H curve. Also, there appears to be a greater discontinuity in both the BSD as well as the L&H corrected data. This is due to the aforementioned ill-conditioned nature of the correction algorithms in these regions.

## 5. COMPARISON BETWEEN THE FSSP CORRECTED SIZE AND THE PDPA

Figure 5.1a shows the percent difference between the FSSP average diameter ( $D_{10}$ ) and the PDPA average diameter as a function of number density. The triangular symbols represent the uncorrected data and the squares represent the L&H total distribution correction. Figure 5.1b is similar to figure 5.1a except it shows the percent difference in the median volume diameter (MVD) as a function of number density.

There are several features to note in figure 5.1a,b. At lower number densities the corrected as well as the uncorrected values of  $D_{10}$  and MVD show a -25% difference with the PDPA measurements. One would expect these values to be closer to each other than 25% since this is a measurement in a low number density spray where the FSSP makes the fewest errors. This 25% difference is attributed to differences in the measured size distributions at diameters less than 10  $\mu\text{m}$ . The PDPA typically counts fewer of these smaller droplets than the FSSP. The question of which instrument is more accurate under these low number density conditions is one of considerable debate.

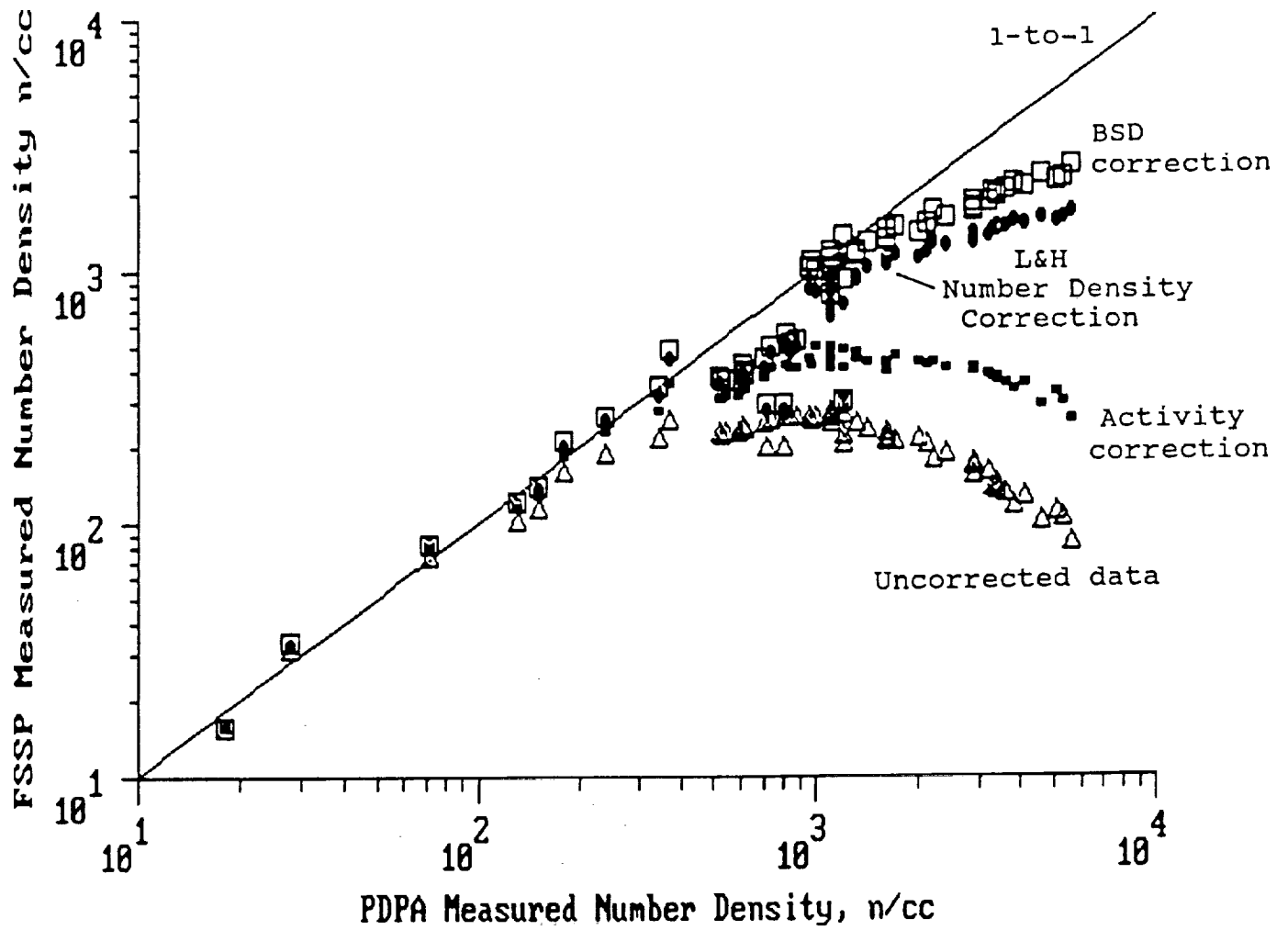
Another feature about figure 5.1a,b is that the percent difference in both the uncorrected FSSP data and the corrected data increases with increasing number density. However the increase is less in the corrected data. For example in figure 5.1b the percent difference between the uncorrected MVD data and the PDPA data is between 0% and -25% up to number densities of 900 /cc. However the corrected FSSP MVD data stays in the 0% to -25% range at number densities approaching 3000 /cc.

It should be noted that the increase in the percent difference between the FSSP and the PDPA data with increasing number density is due to two factors. First, the effect of coincidence events increases the measured size of the uncorrected FSSP data as the number density increases (figure 5.2a triangles). Second, the PDPA data shows a decrease in the measured size with increasing number density (figure 5.2b). Thus, even though the corrected FSSP MVD appears to be independent of number density (figure 5.2a squares), the percent difference between that data and PDPA data increases with number density because the PDPA data shows a definite decrease in measured size as number density increases. It is not known if this decrease is real or an artifact of the PDPA instrument. However, given that the size distribution in a spray is dependent upon the location of the nozzle relative to the probe volume, it is likely that varying number density by repositioning the nozzle also affected the drop size distribution in this experiment.

## 6. CONCLUSION

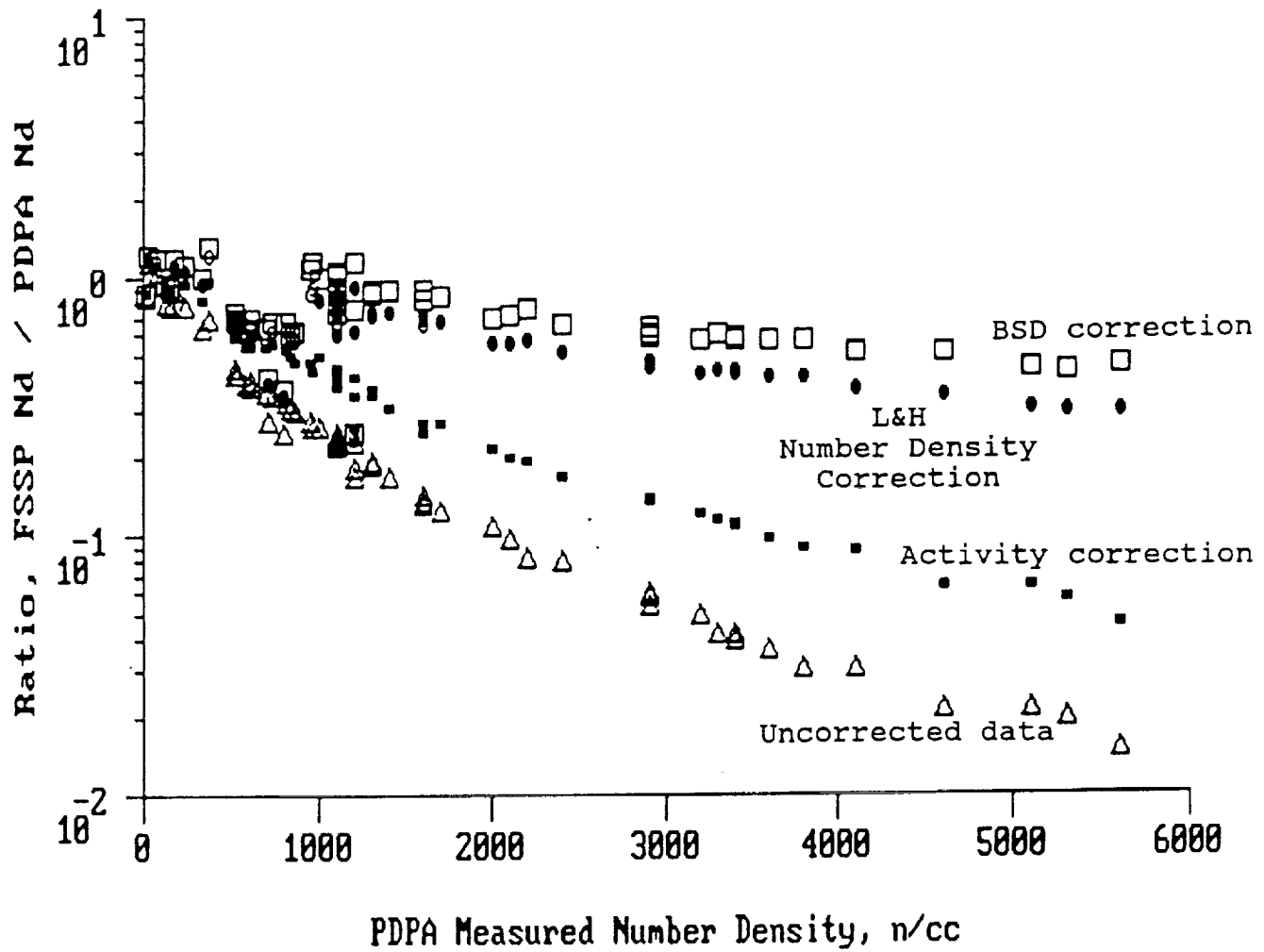
Four FSSP correction algorithms were compared with data taken by the Phase Doppler Particle Analyzer and a prototype optical number density measuring instrument. Three of the algorithms corrected errors in the measured number density. The number density algorithm that compared best to the PDPA data and the NDMI data was the correction algorithm developed by Baumgardner, Strapp, and Dye (ref. 4). Discontinuities in both the BSD corrected data as well as the number density correction algorithm developed by Lock and Hovenac (ref. 12) were reduced by using a value for the laser beam length that was derived from the "maximum measurable number density". An algorithm that corrects sizing errors in the FSSP (ref. 15) was shown to be within 25% of the PDPA MVD data at number densities approaching 3000 /cc.

a

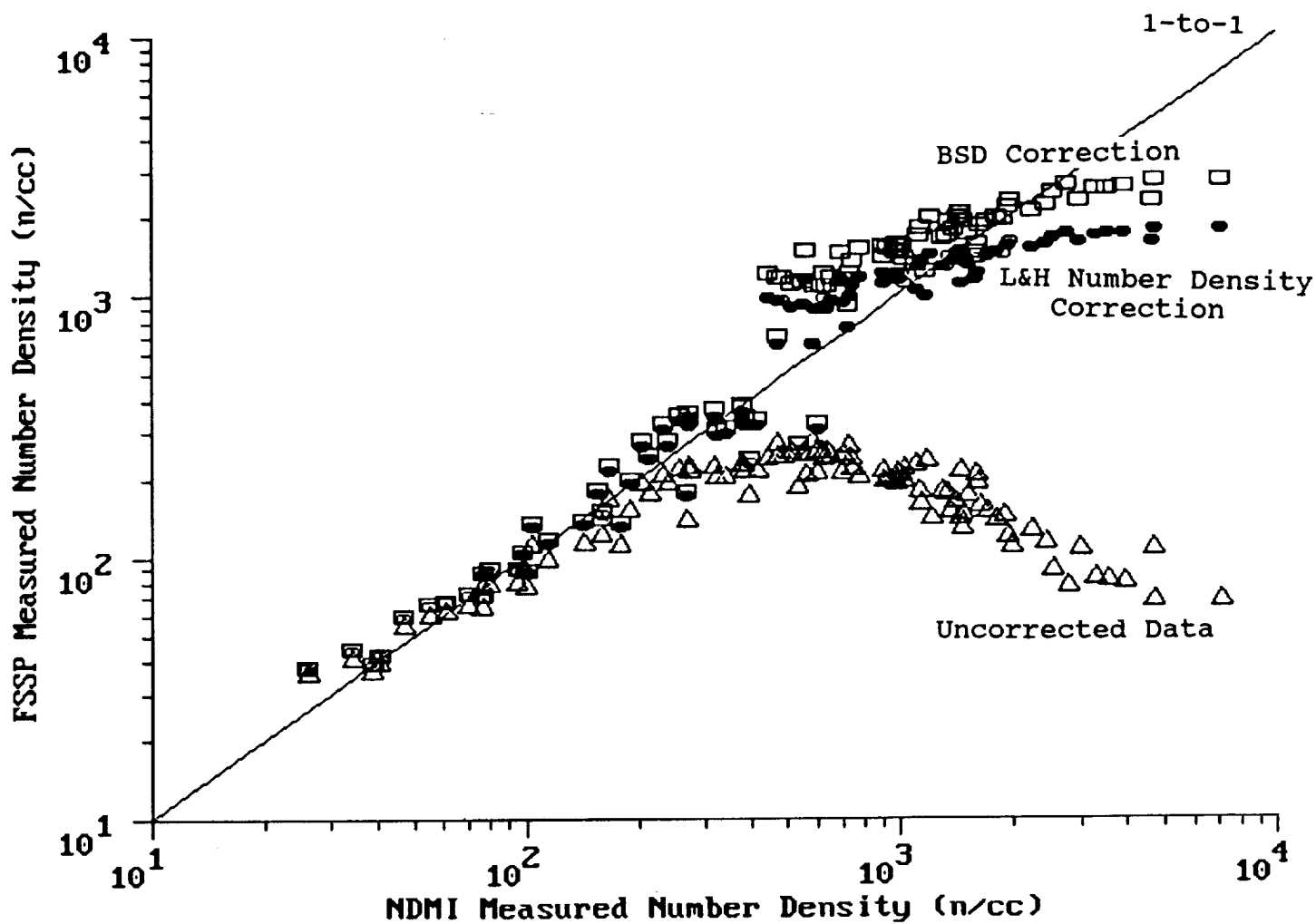


4.2a Comparison of uncorrected number density, the activity correction, the BSD correction, and the L&H correction to the PDPA measured number density.

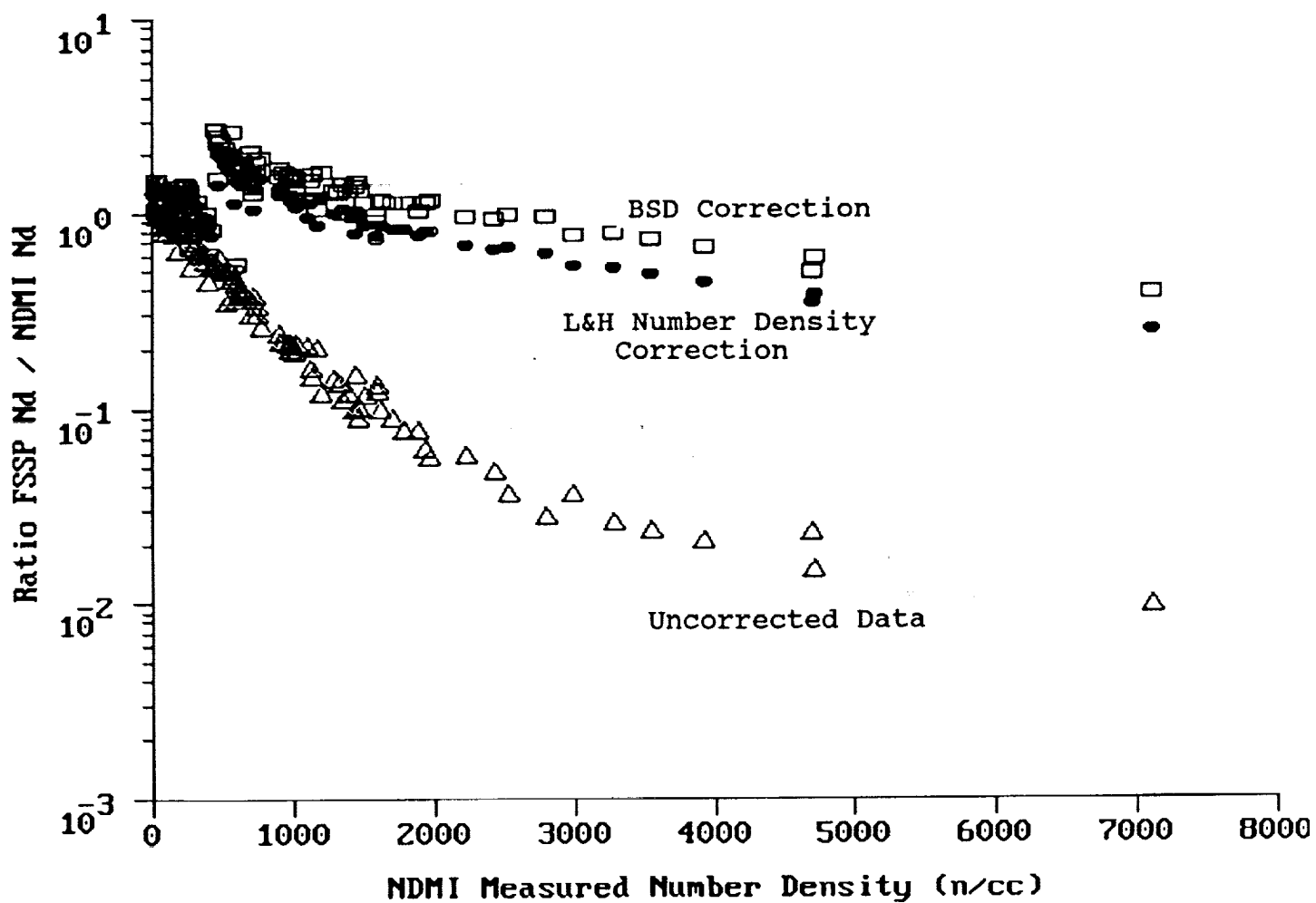
b



4.2b Same data as (a) except the ordinate is plotted as the ratio of the FSSP number density to the PDPA number density.

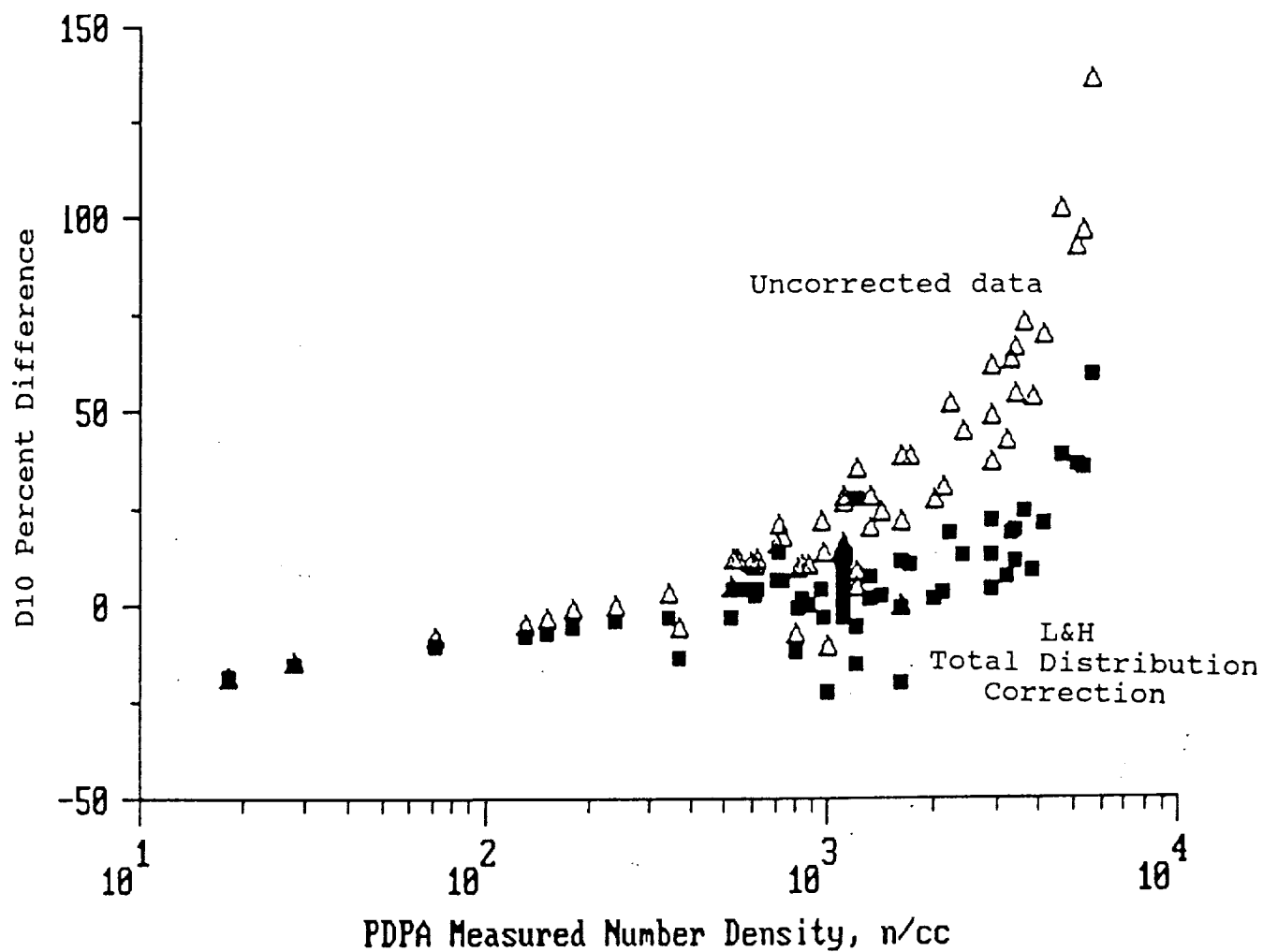


4.2c Comparison of uncorrected number density, the BSD correction, and the L&H correction to the NDMI measured number density.

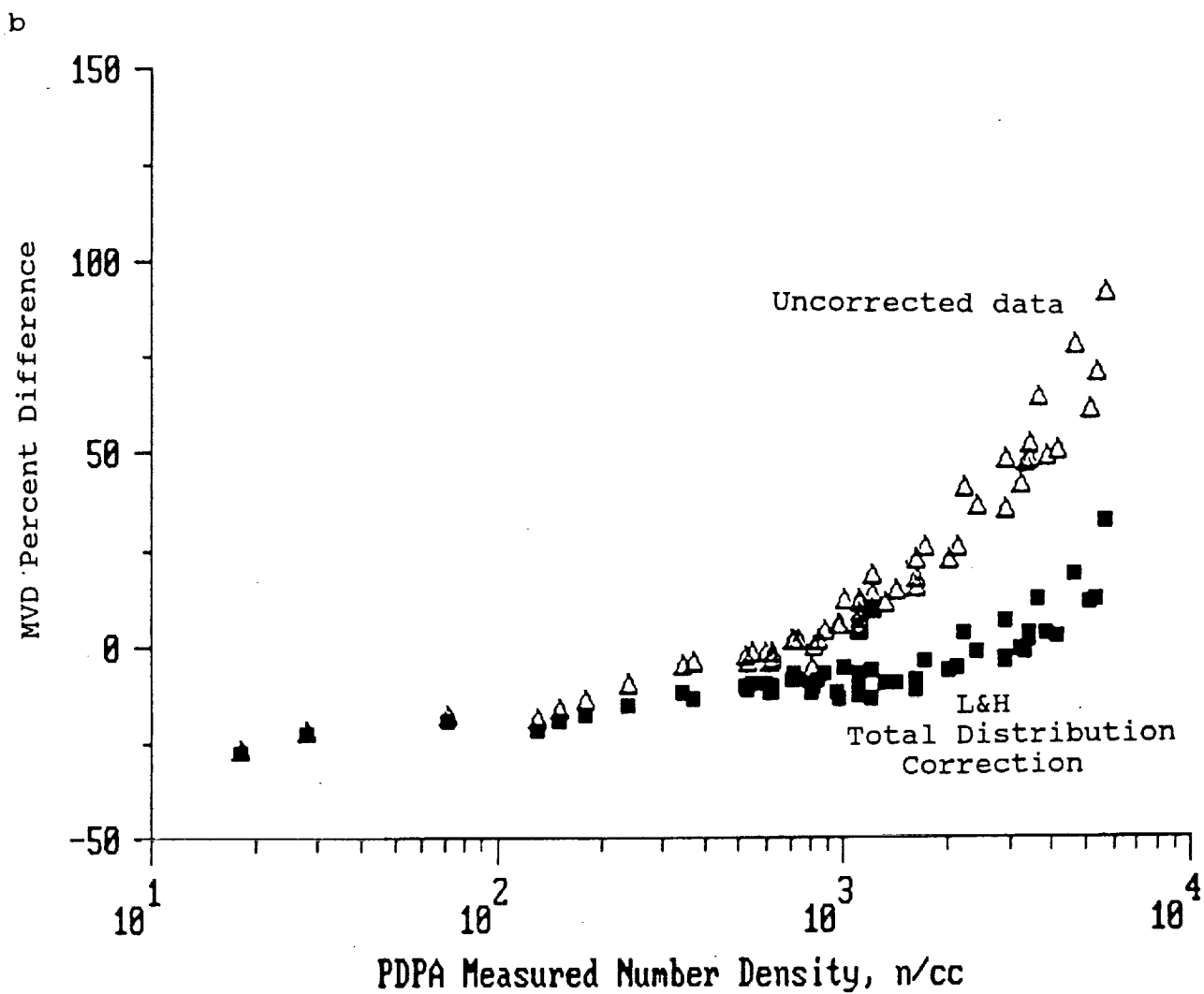


4.2d Same data as (c) except the ordinate is plotted as the ratio of the FSSP number density to the NDMI number density.

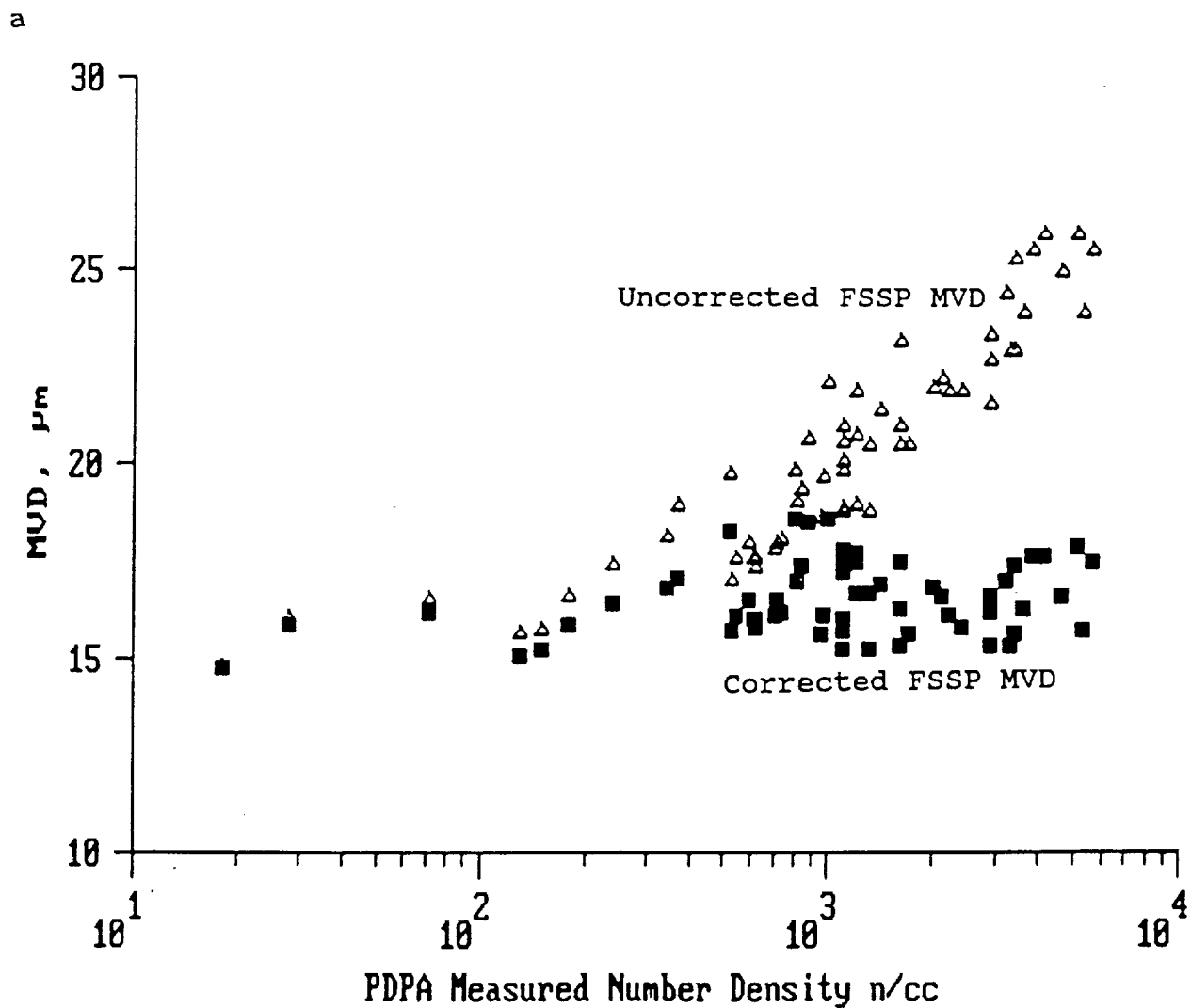
a



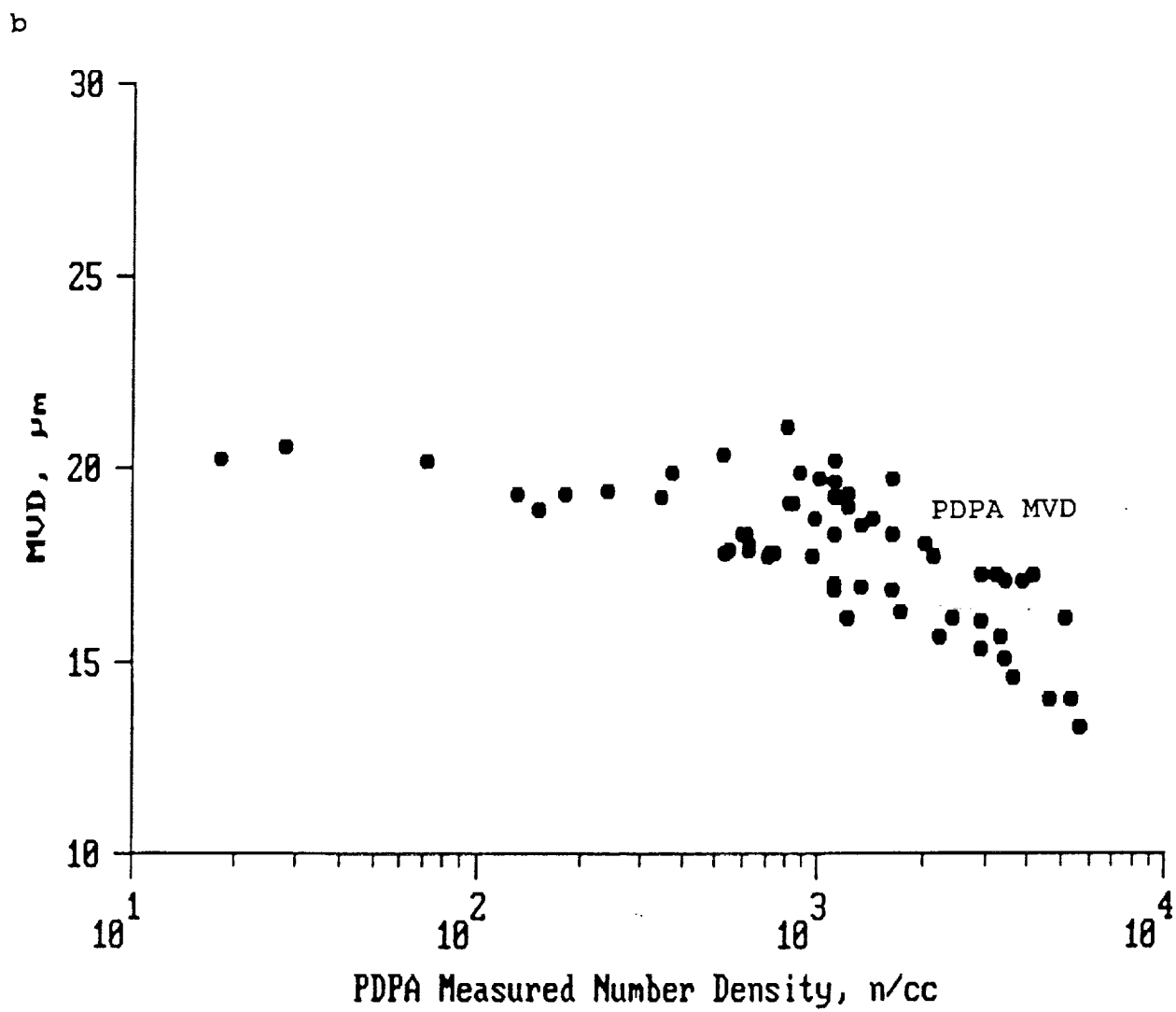
5.1a Percent difference between the FSSP measured average diameter and the PDPA measured average diameter.



5.1b Percent difference between the FSSP measured median volume diameter and the PDPA median volume diameter.



5.2a Uncorrected FSSP MVD data (triangles) increases with number density because of coincidence errors. Corrected FSSP MVD data (squares) shows no increase with number density.



5.2b PDPA MVD data shows a decrease with number density.

## 7. REFERENCES

1. Knollenberg, R.G.: Three New Instruments for Cloud Physics Measurements. Preprints, International Cloud Physics Conference, Boulder, CO, Amer. Meteor. Soc., 554-561, 1976.
2. Hovenac, E.A. and Ide, R.F.: Performance of the Forward Scattering Spectrometer Probe in NASA's Icing Research Tunnel. NASA TM 101381 / AIAA-89-0769, 1989.
3. Forward Scattering Spectrometer Probe: PMS Model 100, Operating and Servicing Manual. Particle Measuring Systems, Inc., Boulder, CO, 1984.
4. Baumgardner, D., Strapp, W. and Dye, J.: Evaluation of the Forward Scattering Spectrometer Probe. Part II: Corrections for Coincidence and Dead-Time Losses. J. Atmos. Oceanic Technol., 2, 626-632, 1985.
5. Cooper, W.A.: Effects of Coincidence on Measurements with a Forward Scattering Spectrometer Probe. J. Atmos. Oceanic Technol., 5, 823-832, 1988.
6. Bachalo, W.D. and Houser, M.J.: Phase/Doppler Spray Analyzer for Simultaneous Measurements of Drop Size and Velocity Distributions. Optical Engineering, 23, 583-590, 1984.
7. Dodge, L.G.: Comparison of Performance of Drop-Sizing Instruments. Applied Optics, 27, 1328-1341, 1987.
8. Durst, F., Melling, A., and Whitelaw, J.H.: Laser Anemometry: A Report on Euromech 36, Journal of Fluid Mech. 56 (1), 143-160, 1972.
9. Cerni, T.A.: Determination of the Size and Concentration of Cloud Drops with an FSSP. J. Climate Appl. Meteor., 22, 1346-1355, 1983.
10. Sonic Development Corp., Parsippany, New Jersey.
11. Stratton Park Engineering Company (SPEC), Inc. 5401 Western Ave., Boulder, Colorado.
12. Lock, J.A. and Hovenac, E.A.: An Improved Correction Algorithm for Number Density Measurements Made with the Forward Scattering Spectrometer Probe. Review of Scientific Instruments, 60 (6), 1143-1153, 1989.
13. Brenguier, J.L. and Amodei, L.: Coincidence and Dead-Time Corrections for Particle Counters. Part I: A General Mathematical Formalism. J. Atmos. Oceanic Technol., 6, 575-584, 1989.

14. Brenguier, J.L. and Amodei, L.: Coincidence and Dead-Time Corrections for Particle Counters. Part II: High Concentration Measurements with an FSSP. J. Atmos. Oceanic Technol., 6, 575-584, 1989.
15. Lock, J.A. and Hovenac, E.A.: A Correction Algorithm for Particle Size Distribution Measurements Made with the Forward Scattering Spectrometer Probe. Review of Scientific Instruments, 60 (6), 1154-1160, 1989.
16. Hovenac, E.A.: Droplet Sizing Instrumentation Used for Icing Research: Operation, Calibration, and Accuracy. NASA CR 182293, DOT/FAA/CT89/13, 1989.
17. Hovenac, E.A. and Hirleman, E.D.: Use of Rotating Pinholes and Reticles for Calibration of Cloud Droplet Instrumentation. J. Atmos. Oceanic Technol., 8, 166-171, 1991.



REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE October 1992	3. REPORT TYPE AND DATES COVERED Technical Memorandum		
4. TITLE AND SUBTITLE Experimental Testing of Four Correction Algorithms for the Forward Scattering Spectrometer Probe		5. FUNDING NUMBERS  WU-505-62-50		
6. AUTHOR(S) Edward A. Hovenac, John R. Oldenburg, and James A. Lock				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191		8. PERFORMING ORGANIZATION REPORT NUMBER  E-7374		
9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, D.C. 20546-0001		10. SPONSORING/MONITORING AGENCY REPORT NUMBER  NASA TM-105906 DOT/FAA/CT-TN 92/29		
11. SUPPLEMENTARY NOTES Edward A. Hovenac, Sverdrup Technology, Inc., Lewis Research Center Group, 2001 Aerospace Parkway, Brook Park, Ohio 44142. John R. Oldenburg, NASA Lewis Research. James A. Lock, Physics Department, Cleveland State University, Cleveland, Ohio 44115. Work partially funded by the Department of Transportation, Federal Aviation Administration, Technical Center, Atlantic City Airport, New Jersey 08405. FAA COTR, James T. Riley, Flight Safety Branch, Federal Aviation Administration.				
12a. DISTRIBUTION/AVAILABILITY STATEMENT  Unclassified - Unlimited Subject Category 35			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words)  Three number density correction algorithms and one size distribution correction algorithm for the Forward Scattering Spectrometer Probe (FSSP) were compared with data taken by the Phase Doppler Particle Analyzer (PDPA) and an optical number density measuring instrument (NDMI). Of the three number density correction algorithms, the one that compared best to the PDPA and NDMI data was the algorithm developed by Baumgardner, Strapp, and Dye (1985). The algorithm that corrects sizing errors in the FSSP that was developed by Lock and Hovenac (1989) was shown to be within 25% of the Phase Doppler measurements at number densities as high as 3000 /cc.				
14. SUBJECT TERMS Aircraft icing; Optics; Instrumentation; Droplet sizing; Laser applications; Cloud physics			15. NUMBER OF PAGES 26	
			16. PRICE CODE A03	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT	